PB82-198417

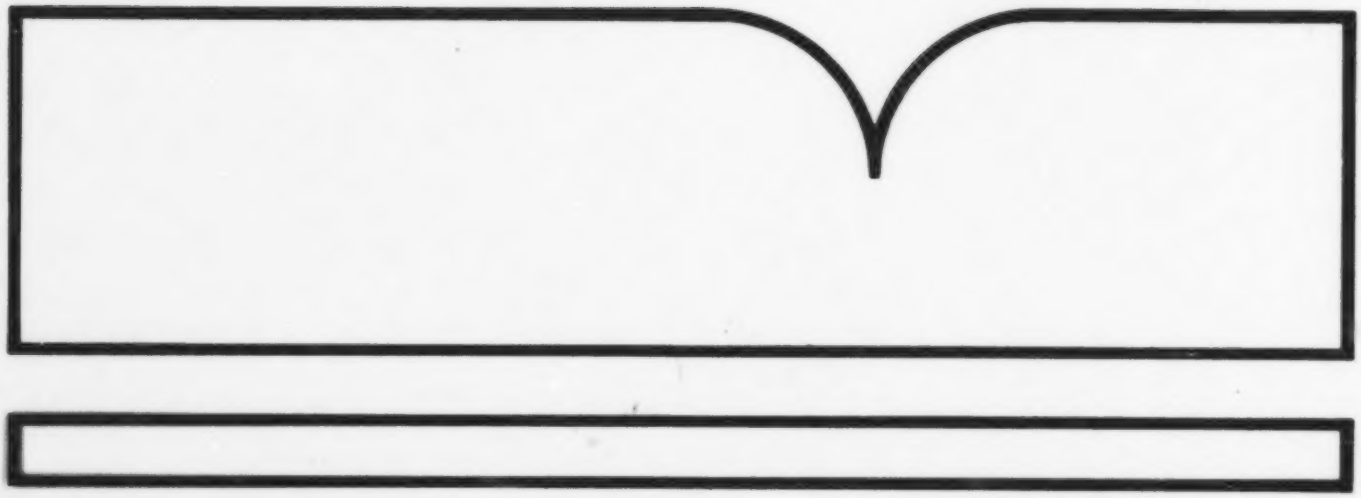
Design, Fabrication and Testing of Ambient Aerosol Sampler Inlets

Research Inst. of Colorado
Fort Collins

Prepared for

Environmental Sciences Research Lab.
Research Triangle Park, NC

Apr 82



U.S. Department of Commerce
National Technical Information Service
NTIS

EPA-600/3-82-039
April 1982

PB82-198417

DESIGN, FABRICATION AND TESTING OF AMBIENT AEROSOL SAMPLER INLETS

by

James B. Wedding and Michael A. Weigand
Research Institute of Colorado
Fort Collins, Colorado 80526

CR806491

Project Officer

Charles W. Lewis
Atmospheric Chemistry and Physics Division
Environmental Sciences Research Laboratory
Research Triangle Park, North Carolina 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-82-039	2. ORD Report	3. RECIPIENT'S ACCESSION NO. PB82 198417
4. TITLE AND SUBTITLE DESIGN, FABRICATION AND TESTING OF AMBIENT AEROSOL SAMPLER INLETS		5. REPORT DATE April 1982 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) James B. Wedding and Michael A. Weigand		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Research Institute of Colorado Fort Collins, CO 80526		10. PROGRAM ELEMENT NO. CDTA1D/01-0416 (FY-82) 11. CONTRACT/GRANT NO. CR806491
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, N. C. 27711		13. TYPE OF REPORT AND PERIOD COVERED Final 5/79 - 10/80 14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Data are presented on the wind tunnel performances of two prototype Inhalable Particulate Matter (IPM) inlets designed for use with a dichotomous sampler. One was developed at the Aerosol Science Laboratory (ASL) Colorado State University, while the other was developed in an independent effort at the University of Minnesota (UM) and Lawrence Berkeley Laboratory (LBL). The ASL inlet is based on a unique omnidirectional cyclone fractionator, described in detail. Over the range of wind speeds from 0.5 - 24 km/hr, its measured 50% cutpoint was virtually invariant, 14.4 - 13.7 μm--well within the presently proposed IPM 50% cutpoint requirement. The UMLBL inlet results indicated near compliance with the IPM performance envelope, but there remain some small differences in data generated by UM and ASL personnel. Enrichment is apparent for both inlets in the 1 - 10 μm particle size range at the highest wind speed. A redesign is underway to eliminate this problem and another related to unfavorable particle deposition patterns on the ASL inlet cyclone. As this report was being completed, a change in D_{50} for IPM from 15 to 10 μm was under serious consideration. While the inlets discussed in this report would then no longer be appropriate, alterations of their design allow adaptation to a new cutpoint choice.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED 20. SECURITY CLASS *(This page)* UNCLASSIFIED	21. NO. OF PAGES 31 22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

DISCLAIMER

This report has been reviewed by the Environmental Sciences Research Laboratory, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

Data are presented on the wind tunnel performances of two prototype Inhalable Particulate Matter (IPM) inlets designed for use with a dichotomous sampler. One was developed at the Aerosol Science Laboratory (ASL), Colorado State University, while the other was developed in an independent effort at the University of Minnesota (UM) and Lawrence Berkeley Laboratory (LBL). The ASL inlet is based on a unique omnidirectional cyclone fractionator, described in detail. Over the range of wind speeds from 0.5 - 24 km/hr, its measured 50% cutpoint was virtually invariant, 14.4 - 13.7 μm -- well within the presently proposed IPM 50% cutpoint requirement. The UMLBL inlet results indicated near compliance with the IPM performance envelope, but there remain some small differences in data generated by UM and ASL personnel. Enrichment is apparent for both inlets in the 1 - 10 μm particle size range at the highest wind speed. A redesign is underway to eliminate this problem and another elated to unfavorable particle deposition patterns on the ASL inlet cyclone. As this report was being completed, a change in D_{50} for IPM from 15 to 10 μm was under serious consideration. While the inlets discussed in this report would then no longer be appropriate, alterations of their design allow adaptation to a new cutpoint choice.

The report was submitted in fulfillment of Cooperative Agreement No. CR806491 by the Research Institute of Colorado under the sponsorship of the U. S. Environmental Protection Agency. This report covers the period May 1, 1979 to October 1, 1980, and active work under the auspices of CR806491 was completed as of September 1, 1980.

CONTENTS

Abstract iii

Figures vi

1. Introduction 1
   History 1
   Present Thinking 2

2. Conclusions and Recommendations 4

3. Proposed IPM Inlet 5
   Design rationale 5
   Design of the cyclone fractionator 6
   Design of the fractionator housing 9

4. Experimental Measurements 10

5. Results and Discussion 12

References 14

Preceding page blank

FIGURES

Number		Page
1	Effectiveness performance envelope for IPM	16
2	Size Selective Hi-Vol	17
3a	Wedding IPM inlet	18
3b	Wedding Inlet (Vane detail)	19
4	ASL Test facility	20
5	Performance curves for Wedding IPM inlet	21
6	Inlets for the dichotomous virtual impactor	22
7	UMLBL IPM inlet	23
8	Performance curves for UMLBL inlet	24

SECTION 1

INTRODUCTION

HISTORY

The effective sampling of aerosols in the ambient atmosphere has received considerable and increasing attention over the past five years. To obtain a representative measurement of the particulate matter present, a sample must be drawn through an inlet device onto a suitable sampling substrate. To provide meaningful data, the inlet must allow all particles of interest to be collected with the same shape of the collection effectiveness curve (see Ref. 1 and Figure 1) independent of sampling conditions. These conditions include ambient wind velocity (magnitude and three-dimensional direction), turbulence scale and intensity, and the presence of extraneous airborne matter (rain, snow, insects). The principal instrument which has been used in the U.S.A. to measure ambient aerosol concentration is the Standard Hi-Vol Sampler, which measures total suspended particulate (TSP) and operates at a flow rate of 1.41 m^3/min (50 cfm). Even though the national ambient air quality standards for particulate matter are defined in terms of TSP (2), this approach can be criticized for a variety of reasons. The collection capability of the samplers has been found to be strongly a function of particle size, wind speed and sampler orientation (see Wedding et al. (1) and the next sub-section) Additionally, characterization of the aerosol concentration becomes nearly impossible when the upper size limit is variable. Hi-Vol samples are not size segregated near the minimum of the bimodal mass distribution (Whitby et al. (3)), which can lead to undesirable chemical reactions between the collected particles, as well as loss of information. Gas to particle conversion can occur on the filter, producing aerosol artifact. Chemical analysis becomes nearly impossible, thus source identification and subsequent control

strategies are limited. These shortcomings prompted the U. S. Environmental Protection Agency in 1972 to examine conventional impactors as a means of fractionating the sample prior to collection. The drawback of particle bounce documented by Dzubay and Stevens (4) led to the adoption of the virtual impaction principle as an appropriate alternative. The single stage version was first described by Hounam and Sherwood (5). Further refinement of the dichotomous sampler resulted from work by Environmental Research Corporation in 1973 - 75 and by Loo et al. (6). In this device, the larger particles travel into a slowly pumped void and are collected on a Teflon filter. The smaller particles, lacking the inertia to penetrate the "virtual surface", are diverted to another collection filter lying on an adjacent horizontal plane. This rationale produces two samples separated into what has been termed respirable vs. non-respirable sizes. Subsequent analysis of samples collected by these devices has revealed a different chemical constituency of the two size modes providing a reasonable basis for the need to segregate samples. Stevens et al. (7) have shown the small particle mode to be acidic--composed mostly of sulfur, lead, bromine and a number of other elements in trace concentrations. The large particle mode is generally basic--composed of a variety of minerals including quartz, limestone, calcite, mica, clay, and trace quantities of tire dust, pollen and lead oxides. Thus, at the present time, there are two basic approaches to the sampling of atmospheric particulate matter: the Hi-vol and the dichotomous sampler.

PRESENT THINKING

Recent EPA emphasis is aimed at developing air quality standards based upon inhalable particulate matter (IPM). Miller et al. (8) define IPM as particles having aerodynamic diameters $\leq$ 15 μm. Inlets for IPM must have well defined large particle cut size characteristics necessitating the usage of a suitable fractionating device to prevent unwanted aerosol from reaching the collection substrates. Figure 1 reveals the present strategy on performance for an acceptable inlet for IPM. The effectiveness of an inlet is defined as the ratio of the mass collected on the sampler substrates to that collected by

an isokinetic sampler, the latter providing the reference on cloud concentration approaching the inlet. The adoption of these D_{50} guidelines (aerodynamic diameter at an effectiveness of 50%) may undergo further change as knowledge increases on the overall effects of various particle sizes to health and environment. Note that the ultimate shape of the fractionating curve has at this point been left quite flexible. However, one would desire an inlet with the curve shape and D_{50} independent of wind speed for consistent sampling. Additionally, the present dichotomous sampler operates at a flow rate of 16.67 L/min with both manual and automatic filter changing options available. The need for size segregating the sample can be questioned, as well as a need for larger flow rates to enable collection of more mass. These thoughts have resulted in the continuing presence of the Hi-vol approach. If one does not wish to fractionate the sample and more mass is desired to be collected in a shorter period of time, a less costly alternative to the dichotomous sampler is the size selective Hi-Vol system. (See Figure 2.) This unit, developed by McFarland et al. (9) under funding by the Environmental Monitoring Sciences Laboratory (EMSL) of the U. S. Environmental Protection Agency, collects particles at a flow rate of 1.13 m^3/min (40 cfm) utilizing the standard glass fiber filter.

This report describes the development of an alternative inlet for the dichotomous sampler, based on a unique omnidirectional cyclone fractionator. This inlet was intended to produce a better match to the presently proposed IPM standard than is realized with current commercially available inlets (12). The present report provides data from the wind tunnel testing of the alternative cyclone inlet. Additionally, measurements are reported on the wind tunnel testing of a second inlet developed independently at the University of Minnesota and Lawrence Berkeley Laboratory, whose design is based on work by Liu and Pui (16).

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

A candidate IPM inlet has been designed, fabricated and wind tunnel tested. On the basis of the tests, it is recommended as a reasonable choice for use on EPA's IPM dichotomous sampler network. A new completely revised fractionator and inlet housing concept are presently being designed and tested specifically to eliminate an enrichment condition exhibited by the inlet and to improve the performance characteristics of the cyclone fractionator by causing the mass to deposit in more favorable locations and to make the unit more compact and versatile. The re-design was initiated in December 1980 under a different project and is continuing.

Wind tunnel testing was performed on a second inlet provided by the University of Minnesota and Lawrence Berkeley Laboratory. While the tests showed the UMLBL inlet to be in near compliance with the presently proposed IPM performance envelope, independent measurements at the University of Minnesota have shown a slightly better performance. The differences between the two sets of measurements, although small, remain unresolved and may be indicative of the degree of uncertainty in such measurements at the present time.

The technology represented by either of these inlets does not purport to be the ultimate answer to IPM sampling needs. As health effects and other environmental factors and national/scientific needs dictate changes in monitoring strategies (i.e., D_{50}, flow rates), other inlet systems will need to be developed. As this report was being completed, a change in D_{50} for IPM from 15 to 10 μm was under serious consideration. While the inlets discussed in this report would then no longer be appropriate, alterations of their design allow adaptation to a new cutpoint choice.

SECTION 3

PROPOSED IPM INLET

DESIGN RATIONALE

The design rationale is based upon the need for an ambient aerosol sampling inlet capable of collecting all particles of interest with the same D_{50} and shape of the collection effectiveness curve vs. aerodynamic diameter independent of the sampling conditions. An inlet for IPM must at this time meet the criteria illustrated in Figure 1. The resulting effectiveness curve of an inlet system is the product of the fractionating device efficiency used to establish the desired D_{50} and the efficiency of the inlet geometry which transports the aerosol to the fractionator and protects the system from environmental factors. As it is not practical or necessary to achieve isokinetic sampling in the field, the inlet must only transport to the fractionating device the particle sizes of interest with consistent or predictable losses independent of fluid mechanics (wind speed, three-dimensional direction, turbulence intensity and scale) and environmental conditions (precipitation, insects, etc.). Thus, separated flow regions within the device must be avoided as these areas will cause varying deposition loss as a function of fluid energy. The inlet geometry must serve to self-limit the number of entering fluid streamlines commensurate with the approach flow velocity so as to attain an aerosol sample whose mass and size range of interest is independent of the fluid mechanics and environmental factors.

The choice of the fractionation device is practically limited to a conventional impactor, virtual impactor, or a cylcone. The conventional impactor suffers from particle bounce problems which may be reduced for a time

with an appropriate coating, but will require unpredictable periodic maintenance. The virtual impactor may be a candidate, but to date no workable prototypes have emerged. The cyclone, if designed to be omnidirectional would appear to be the best candidate as the slope of the fractionation curve is comparable to that of an impactor. It possesses a potentially large surface area for deposition, and it has considerably less susceptibility, if any, to particle bounce. Note that no force of sufficient magnitude exists to cause re-entrainment or bounce from the surface of a cyclone unless that particle were elastic enough to add energy to the particle phase during the particle-wall collision. A particle of this nature would not represent those commonly found in the atmosphere. It is for these reasons that the cyclone approach was adopted for this proposed IPM inlet.

DESIGN OF THE CYCLONE FRACTIONATOR

As shown in Figure 3a, this cyclone is unique. It is omni-directional allowing the aerosol entry from any angle of approach. An angular impetus is imparted to the particle motion via the eight evenly spaced entrance vanes. Details of the vane structure are shown in Figure 3b. The body of the cyclone is cylindrical in cross section.

As the particle enters the cyclone (see Figure 3a), it follows the circular path defined by the vanes and accelerates toward the outer radius of the cyclone defined by R_2. The particle arrives at R_2 with the velocity U_o where it begins its upward ascension at velocity U_v. If the particle is not removed, it will travel the distance ℓ, negotiate the turn at R_1 and travel downard through the exhaust tube to the exit plane of the inlet. Particles that are removed are intended to deposit on the inside collector surface as shown in Figure 3a. It has been shown in subsequent tests that a large percentage of the mass had deposited on the vane assembly and exhaust tube. A redesign of the fractionator, begun in July, 1980 and not as yet complete, has indicated that this problem can be totally resolved, resulting in a much more compact design and one in which virtually all the mass is deposited on the inlet tube surface.

There exists no proven workable model for predicting the performance of a cyclone at present. A particle traveling in the flow will drift outward along the radius under the influence of centrifugal force, opposed by Stokes drag force. (The particle will also settle due to gravity.) Equating the centripetal and centrifugal forces gives

$$\frac{m V_t^2}{r} = \frac{3\pi \mu D}{C} V_r \qquad (1)$$

where:

m = particle mass

r = radial position of particle

C = Cunningham factor ~ 1 in this case

D = minimum particle diameter that will pass through the cyclone

V_t = tangential velocity, annular region between R_1 and R_2

V_r = radial velocity

μ = coefficient of viscosity

An expression for the tangential velocity distribution when $h = R_2 - R_1$ (see Figure 3a) is reasonably represented from the early work of Sheppard and Lapple (10) as

$$V_t = \frac{U_o}{(R_2/r)^n} \qquad (2)$$

where r is the radial component and U_o the velocity at R_2. Setting n = 1 from Sheppard and Lapple (10), which assumes that the velocity profile can be represented via application of rigid body mechanics, and noting that $V_r = dr/dt$, and combining equations 1 and 2 gives

$$\int_{r_e}^{R_2} \frac{dr}{r} = \frac{\rho D^2 U_o^2}{18\mu R_2^2} \int_o^{t_d} dt \qquad (3)$$

where:

ρ = particle density

r_e = radius of curvature when the particle enters the cyclone

t_d = time for particle to deposit i.e., reach R_2

Integrating (3) results in

$$t_d = \frac{R_2^2 \ 18 \ \mu}{\rho D^2 U_o^2} \ \ell n \left(\frac{R_2}{r_e} \right) \qquad (4)$$

t_d may also be expressed by

$$t_d = \frac{2\pi R_2 S}{U_o} \qquad (5)$$

where S = number of spirals the particle makes prior to deposition. Setting (4) equal to (5) and solving for D, one obtains

$$D = 1.69 \left[\frac{R_2 \ \mu}{\rho U_o S} \ \ell n \left(\frac{R_2}{r_e} \right) \right]^{1/2} \qquad (6)$$

Letting $r_e = 0.5 \ R_2$ for S = 1.5 (from tests using dyes which indicate that the particles make 1.5 turns before depositing) one obtains a D = 26.5 μm which is also the extrapolated value obtained from Figure 5. Note that this curve includes the effect of the inlet housing efficiency. Laboratory experiments on the fractionator alone indicate $r_e = 0.71 \ R_2$ is more correct for predicting the performance of the cyclone.

Two other expressions were utilized to complete the cyclone design. One was

$$t_{tr} = \frac{\pi h}{Q} (R_s^2 - R_2^2) \qquad (7)$$

where Q is the inlet flow rate, and t_{tr} is the transport time from R_s to R_2 (see Figure 3a) in order to calculate settling losses. The other expression was

$$t_{res} = \ell/U_v \qquad (8)$$

which is the residence time of a particle within the cyclone · t_d, equation (5), was set conservatively at 1.5 t_{res}.

The present design allows a potential collection area of over 200 cm^2 and an additional volume for storage of collected particulate matter exceeding 500 cm^3. This unit should be capable of operating in the field maintenance-free for a considerable period of time, but mass depositing on the center exhaust tube could become dislodged if struck sufficiently hard, causing unwanted mass to deposit on the collection substrate.

DESIGN OF THE FRACTIONATOR HOUSING

Figure 3a shows the bell-shaped housing and lower radius similar in concept to the inlet developed at the Aerosol Science Laboratory in the summer of 1975 (see Wedding et al. (1), McFarland et al. (11)) and later sold comercially by Sierra and Beckman (Figure 6). The design of Figure 3a is a modification of these units following the theoretical predictions from the model presented by Wedding et al. (12). This approach was adopted after other techniques failed to satisfy performance criteria or would prove susceptible to environmental factors. Additionally, the approach has a wealth of data available on its performance as well as a predictable model.

SECTION 4

EXPERIMENTAL MEASUREMENTS

The Wedding IPM inlet (Figure 3) and the UMLBL inlet (Figure 7) were tested in the closed loop Aerosol Science Laboratory Wind Tunnel at Colorado State University (Figure 4). The tunnel has a cross-sectional dimension of 1.22 m square at the test section. The longitudinal component of turbulence intensity at the test location was found by hot-wire anemometer measurements to be 4%. Similarly, the longitudinal macroscale was about 20 cm, and the vertical macroscale was < 2 cm. The tests utilized monodisperse aerosols with nominal aerodynamic diameters of 7 to 20 μm generated by a vibrating orifice atomizer operating in an inverted manner. Particles employed in the study were made from an oleic acid-ethanol mixture tagged with uranine. The aerosol was sized both by calculation and microscopically. The spread factor, or ratio of measured to aerodynamic diameter, of oleic acid for this size range on oil phobic (coated with 3M fluorocarbon) glass slides has been found on the average to be 1.39. Measurements of doublets utilizing a Casella impactor in the system have been found not to exceed 4% at the test section. Aerosol from the atomizer was injected through a 15.24 cm-diameter pipe containing a Kr-85 charge neutralizer. The pipe diverged into the annular region between two cones. Six pipes spaced around the annular region led the aerosol into the tunnel. This injection system produced a particle concentration profile across the test section which was found to be independent of wind speed over the range of 0.5 to 40 km/hr. Variation of the concentration across the width of the inlet never exceeded 12.2%.

The Wedding inlet was tested at wind speeds of 0.5, 2, 8 and 24 km/hr, and the UMLBL Inlet at 2, 8 and 24 km/hr. The velocities were measured upstream of the test section with a calibrated hot-wire anemometer (Andersen

air velocity meter). The anemometer was calibrated using a precision pitot tube and micromanometer. To determine the inlet effectiveness, the aerosol concentration was measured before and after each test using a sampling manifold 0.90 m wide with six isokinetic sampling nozzles spaced at equal intervals (~15 cm) in the same horizontal plane and at the same location in the test section as the inlet opening. Each nozzle led to a 47 mm Gelman AE glass fiber filter. The inlet was mounted on a vertical tube approximately 1 m long sealed to a Millipore filter holder on the bottom. The sampling effectiveness of the inlet was determined by comparing the quantity of aerosol passed by the inlet and deposited on the filter to that collected by the isokinetic sampling with appropriate corrections for differences in sampling volume and pressure drops as monitored in the lines. Collection substrates were washed in 50 ml of pure ethanol, then diluted 1:1 with distilled deionized water which served as a buffer to stabilize fluorescence. A 4 ml aliquot of each sample solution was measured for uranine content with an Aminco fluorometer.

SECTION 5

RESULTS AND DISCUSSION

Results of the wind tunnel tests on the sampling effectiveness of the Wedding inlet are shown in Figure 5, and the UMLBL Inlet in Figure 8. The UMLBL Inlet test results at 0.5 km/hr are not included as they are inconclusive. Each plotted point represents the average value of at least eight data points taken on different days. Note the error bars on the data. Tests are quickly and reproducibly performed for speeds of 2 - 24 km/hr (and greater). For the 0.5 and 2 km/hr tests there is insufficient fluid energy to adequately mix the injected aerosol -- thus the greater error potential must be noted. Figure 5 shows the results of the inlet shown in Figure 3. Except for an enrichment condition below 10 μm at 24 km/hr the measurements fall within the IPM performance envelope. All curves generated at the various wind speeds are essentially parallel curves from the D_{50} point and larger. The D_{50} values at 0.5, 2, 8 and 24 km/hr are 14.4, 14.0, 14.2, 13.7 μm, respectively. Though not mathematically rigorous, both $\sigma_{g_{84}}$ and $\sigma_{g_{16}}$ are noted as they are not identical.

Independent tests on solid particle bounce by Dr. John at the Air and Industrial Hygiene Laboratory indicated the following: "The inlet as shown in Figure 3 exhibits negligible solid particle bounce" (13).

Studies are also needed to test the instrument for effectiveness with mean velocities at different angles with respect to the horizontal plane, at different levels of turbulence scale and intensity, and under conditions of simulated rainfall in air moving at 24 km/hr and higher.

Note that, as mentioned earlier, the fractionator and housing are in the process of a total redesign at present.

The UMLBL inlet results are given in Figure 8. Within experimental error the measurements fall within the IPM performance envelope, except for the 5 μm points at 2 and 24 km/hr. Independent measurements performed at the University of Minnesota showed a virtually identical enrichment at 24 km/hr, but all measurements at 1 km/hr were within the limits of the IPM performance envelope (14). The differences between the two sets of measurements, although small, are unresolved at present.

The collection effectiveness under ambient conditions of the commercial dichotomous sampler inlet, the UMLBL inlet, and an inlet similar to that of Figure 3 have been compared in an extensive series of measurements performed at Research Triangle Park, NC. The results are available elsewhere (17).

REFERENCES

1. Wedding, J. B., A. R. McFarland and J. E. Cermak, "Large Particle Collecton Characteristics of Ambient Aerosol Samplers", Env. Sci. and Tech. 11, 387 (1977).

2. Federal Register, "National Primary and Secondary Ambient Air Quality Standards", Vol. 36, No. 84, Friday, April 30, Part II (1971).

3. Whitby, K. T., R. B. Husar and B. Y. H. Liu, Journal Colloid Interface Sci. 39, 177 (1972).

4. Dzubay, T. G., R. K. Stevens and C. M. Peterson, "Applications of the Dichotomous Sampler to the Characterization of Ambient Aerosols", in X-Ray Fluorescence Analysis of Environmental Samples, T. G. Dzubay (ed.), 95, Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan (1977).

5. Hounam, R. F. and R. J. Sherwood, "The Cascade Centripeter: A Device for Determining the Concentration and Size Distribution of Aerosols", Am. Ind. Hyg. Assoc. 26, 122 (1965).

6. Loo, B. W., J. M. Jaklevic and F. S. Goulding, "Dichotomous Virtual Impactors for Large-Scale Monitoring of Airborne Particulate Matter", LBL-3854, May 1975.

7. Stevens, R. K., T. G. Dzubay, G. Russwurm and D. Rickel, "Sampling and Analysis of Atmospheric Sulfates and Related Species", Atm. Environ. 12, 55 (1978).

8. Miller, F. J., D. E. Gardner, J. A. Graham, R. E. Lee, Jr., W. E. Wilson and J. D. Bachmann, "Size Considerations for Establishing a Standard for Inhalable Particles", J. Air. Pollut. Control Assoc. 29, 610 (1979).

9. McFarland, A. R., C. A. Ortiz and C. E. Rodes, "The Size Selective Inlet for the Hi-Vol Sampler", Air Quality Laboratory, Texas A&M University, College Station, Texas, Publ. 3565/03/80/ARM (1980).

10. Sheppard, C. B. and C. E. Lapple, "Flow Pattern and Pressure Drop in Cyclone Dust Collectors", Ind. and Eng. Chem., August, 972 (1939).

11. McFarland, A. R., J. B. Wedding and J. E. Cermak, "Wind Tunnel Evaluation of a Modified Andersen Impactor and an All Weather Sampler Inlet," Atm. Environ. 11, 535 (1977).

12. Wedding, J. B., M. Weigand, W. John and S. Wall, "Sampling Effectiveness of the Inlet to the Dichotomous Sampler", Env. Sci. and Tech., 14, 1367 (1980).

13. John, W., Private Communication, Air and Industrial Hygiene Laboratory, California Department of Health, Berkeley, CA 80226, March 1980.

14. Liu, B. Y. H., Private Communication, University of Minnesota, Minneapolis, MN, Jan 1981.

15. Ranade, M. B. and E. R. Kashdan, "Critical Parameters for the Federal Reference Method for the Inhalable Particulate Standard", Final Report Technical Directive 222, EPA Contract 68-02-2720, Research Triangle Institute, Research Triangle Park, N. C. (Sept. 1979).

16. Liu, B. Y. H. and D. Y. H. Pui, "Aerosol Sampling Inlets and Inhalable Particles", Atm. Environ. 15, 589 (1981).

17. Shaw, R. W., R. K. Stevens, C. W. Lewis and J. H. Chance, "Comparison of Aerosol Sampler Inlets", Paper 81-5.3, Air Pollution Control Association 74th Annual Meeting, June 21 - 26, 1981, Philadelphia.

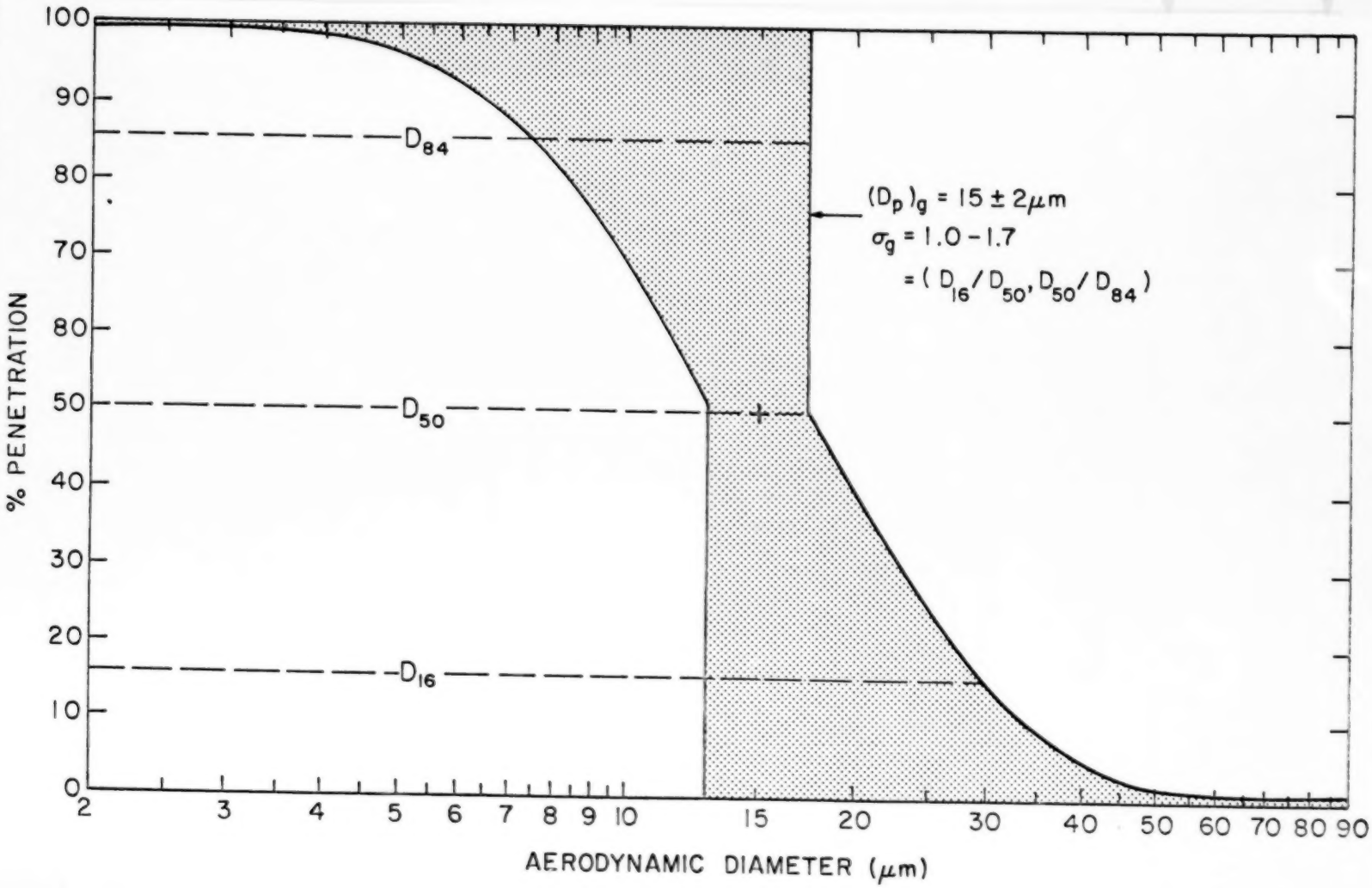


Figure 1. Effectiveness Performance Envelope for IPM, Ranade and Kashdan (15)

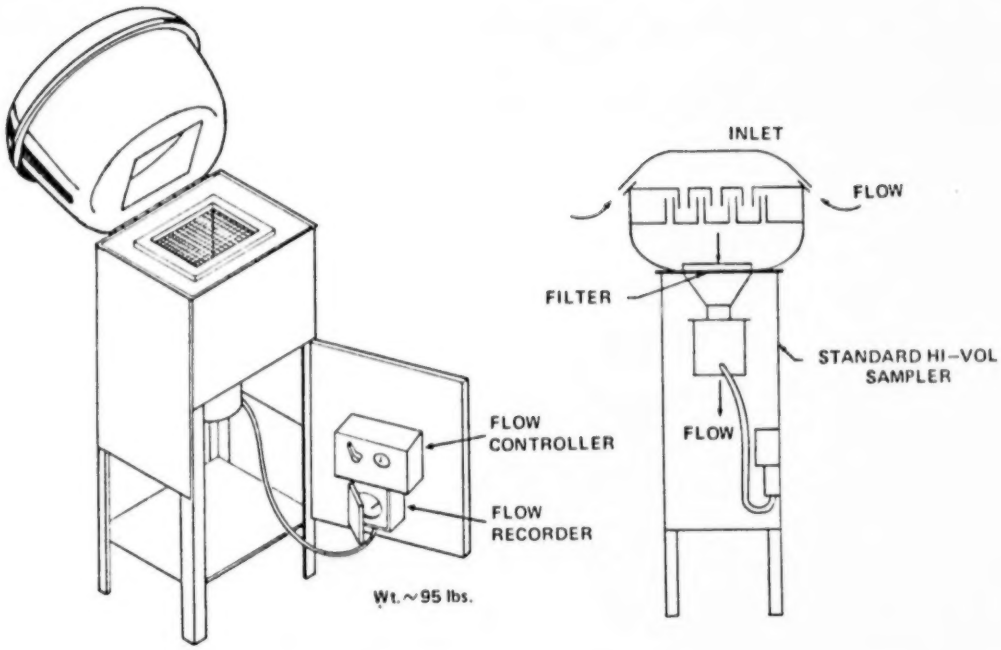


Figure 2. Size Selective Hi-Vol, McFarland et al. (9)

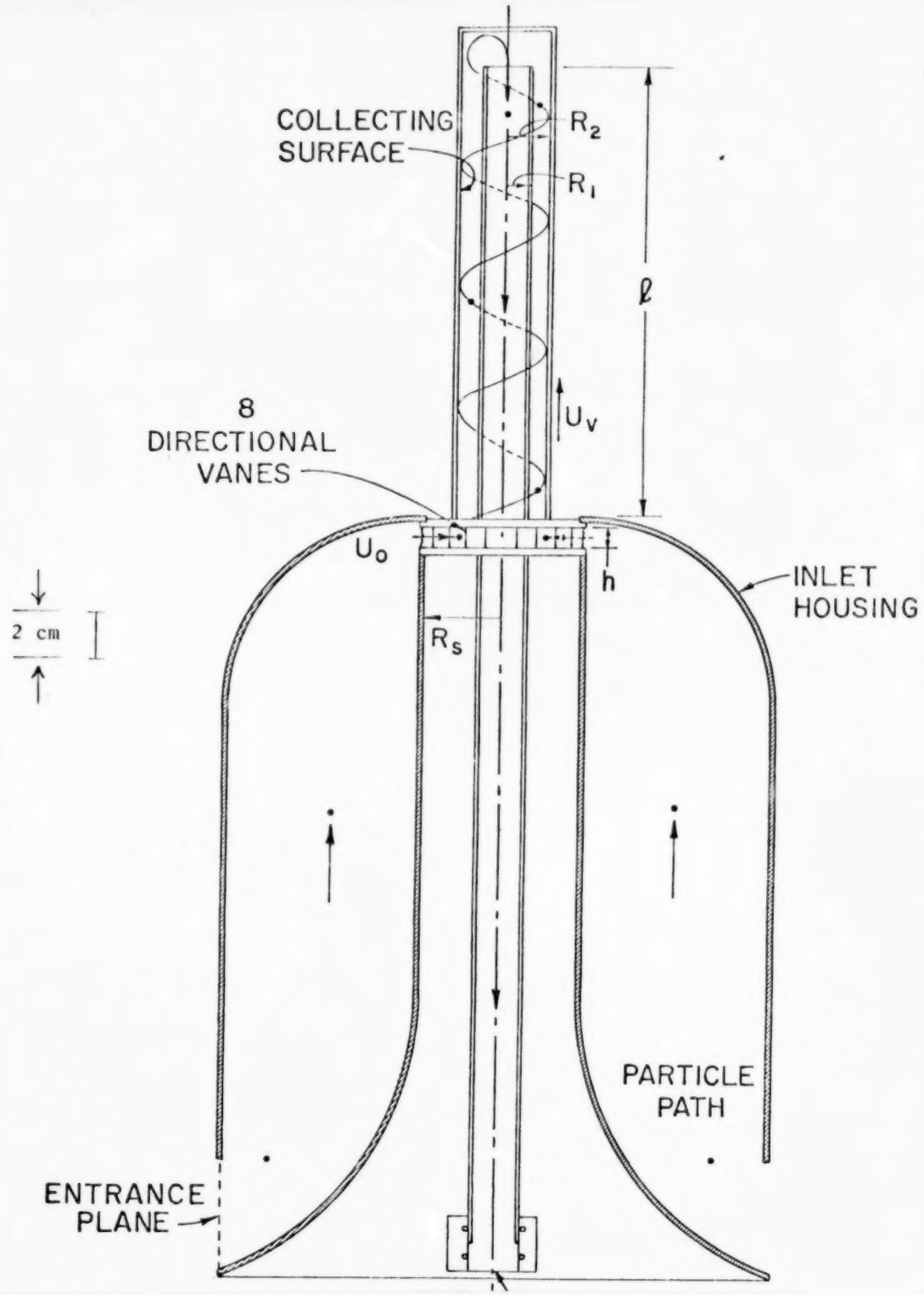


Figure 3a. Wedding IPM Inlet

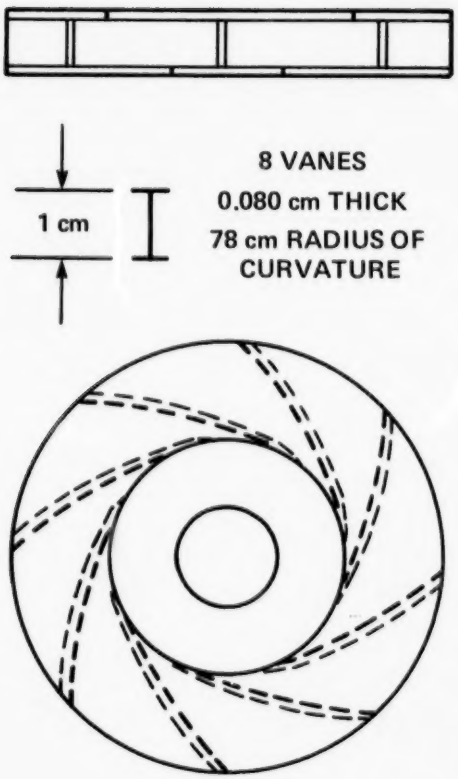


Figure 3b. Wedding Inlet (Vane detail)

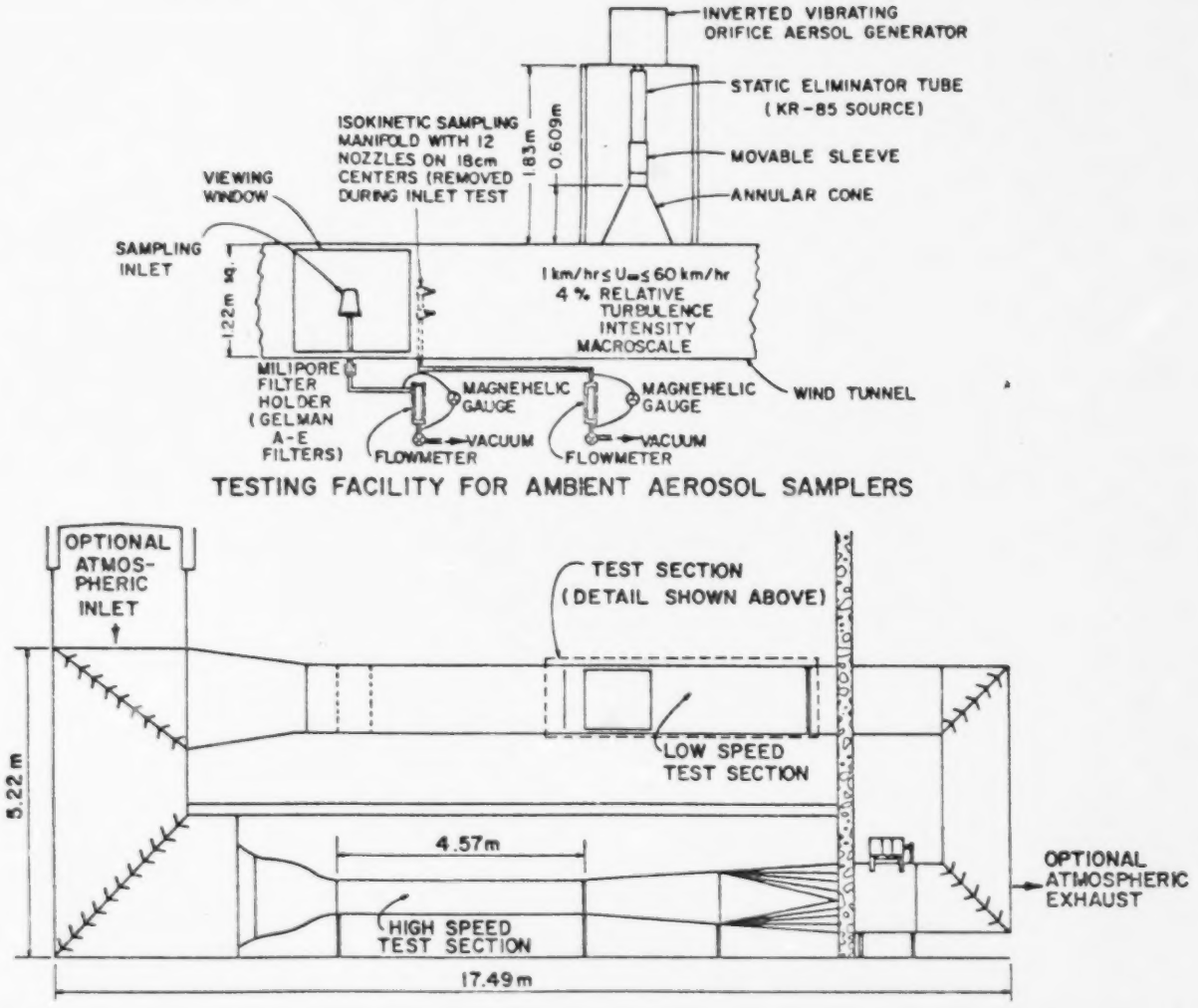


Figure 4. Aerosol Science Laboratory Test Facility, Colorado State University

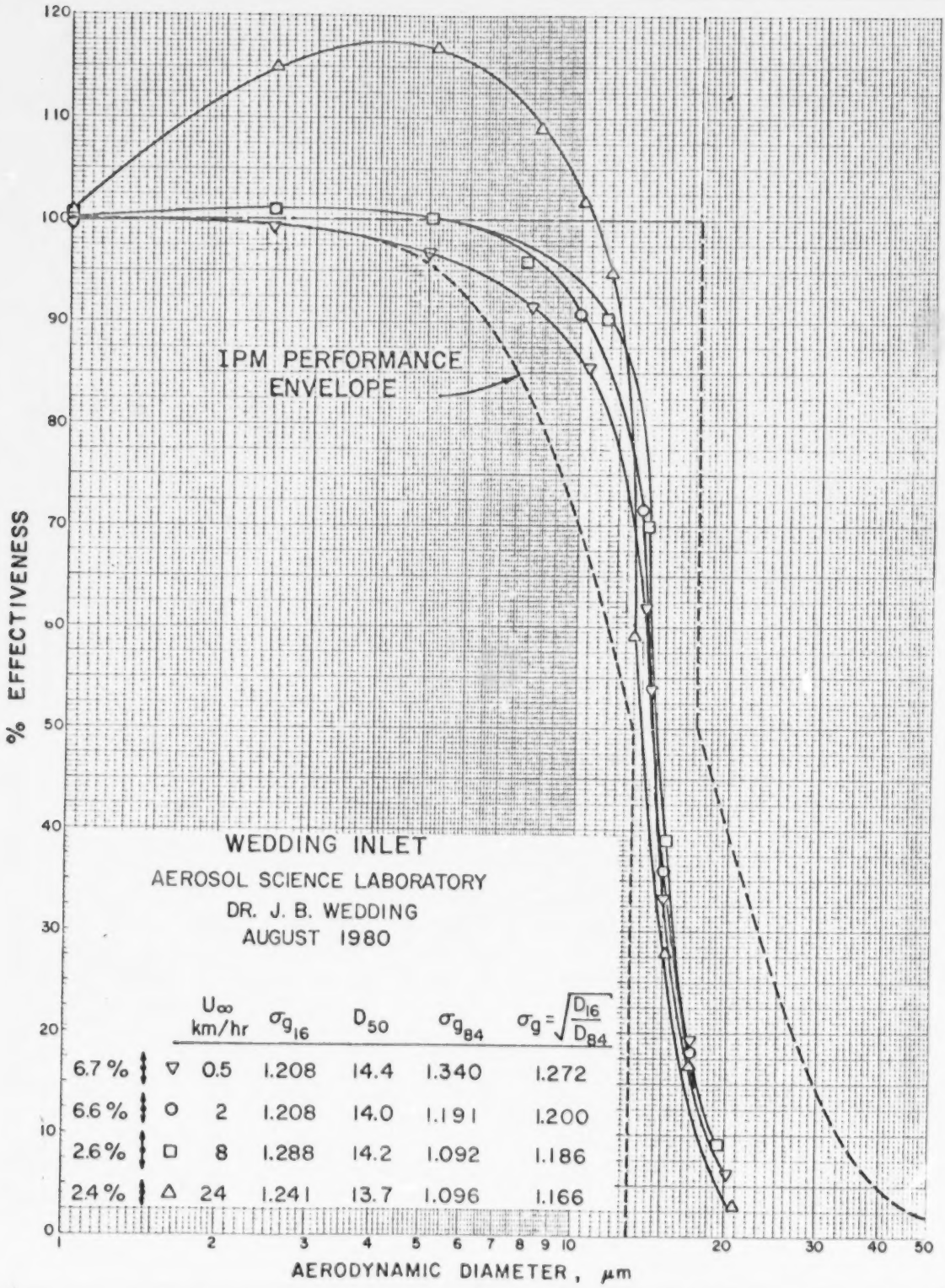


Figure 5. Performance Curve for Wedding IPM Inlet with D_{50} - 15 μm

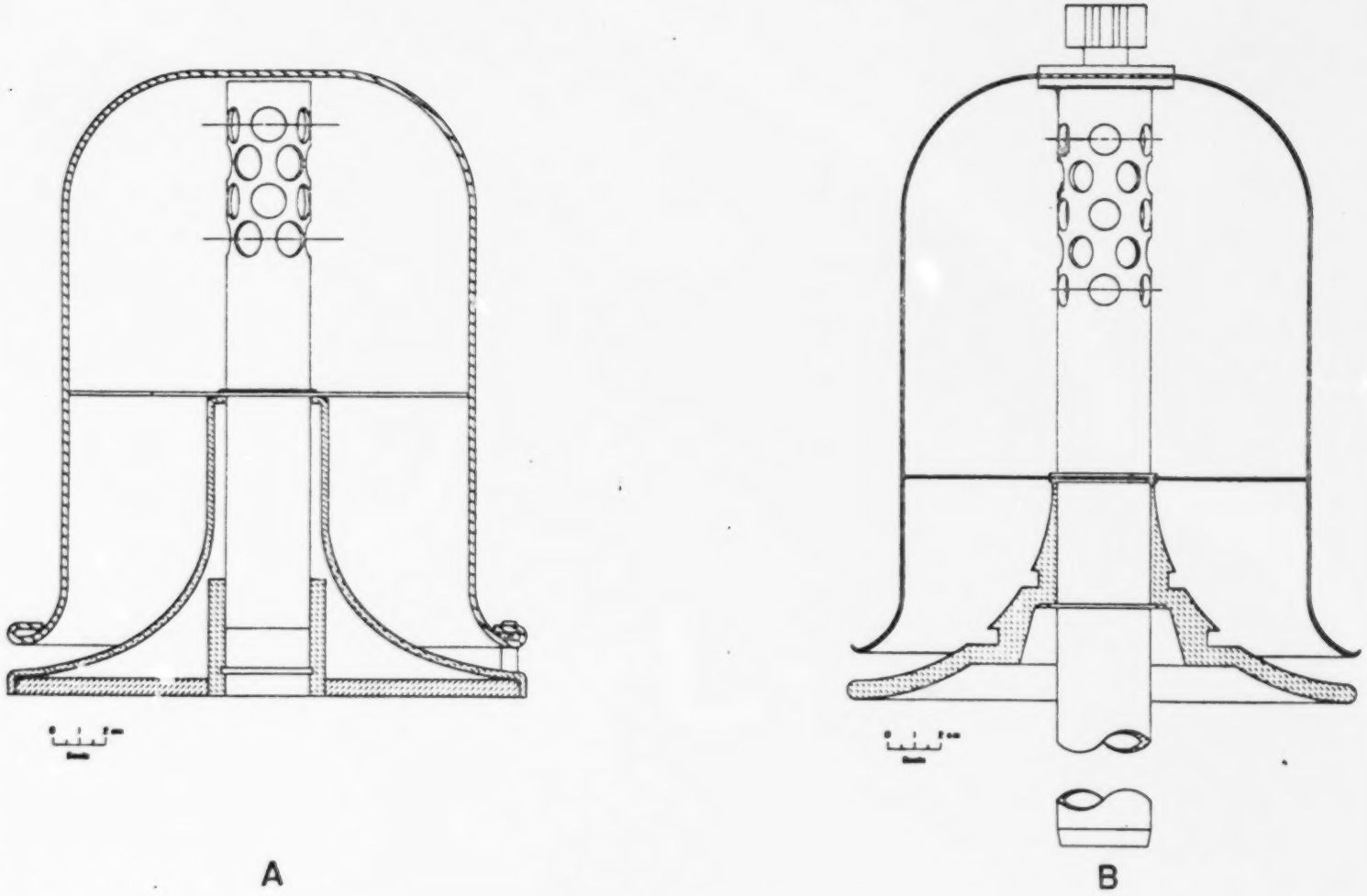
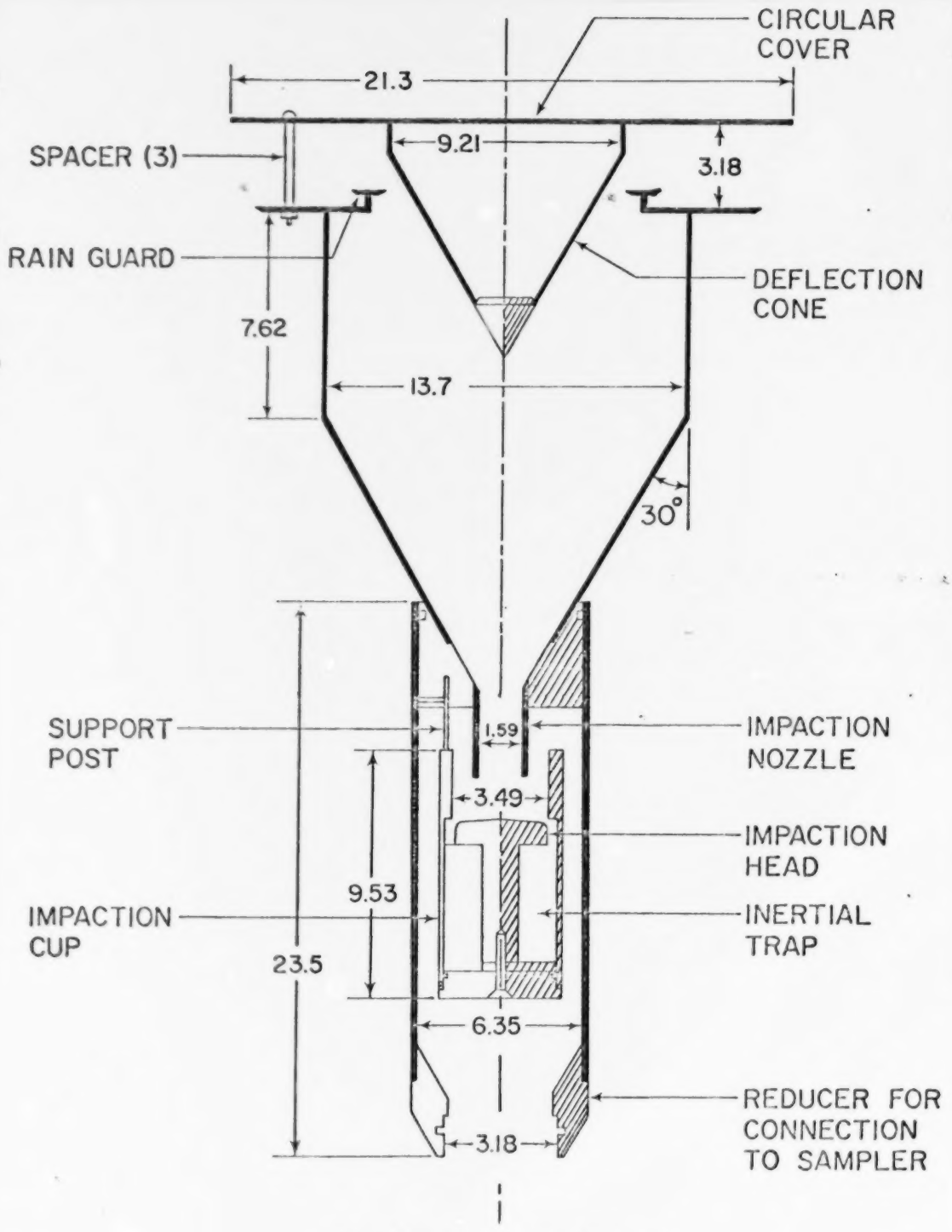


Figure 6. Inlets for the Dichotomous Virtual Impactor (a) Sierra 244E, (b) Beckman, Wedding et al. (1), McFarland (11)



All Dimensions in Centimeters

Figure 7. UMLBL Inlet

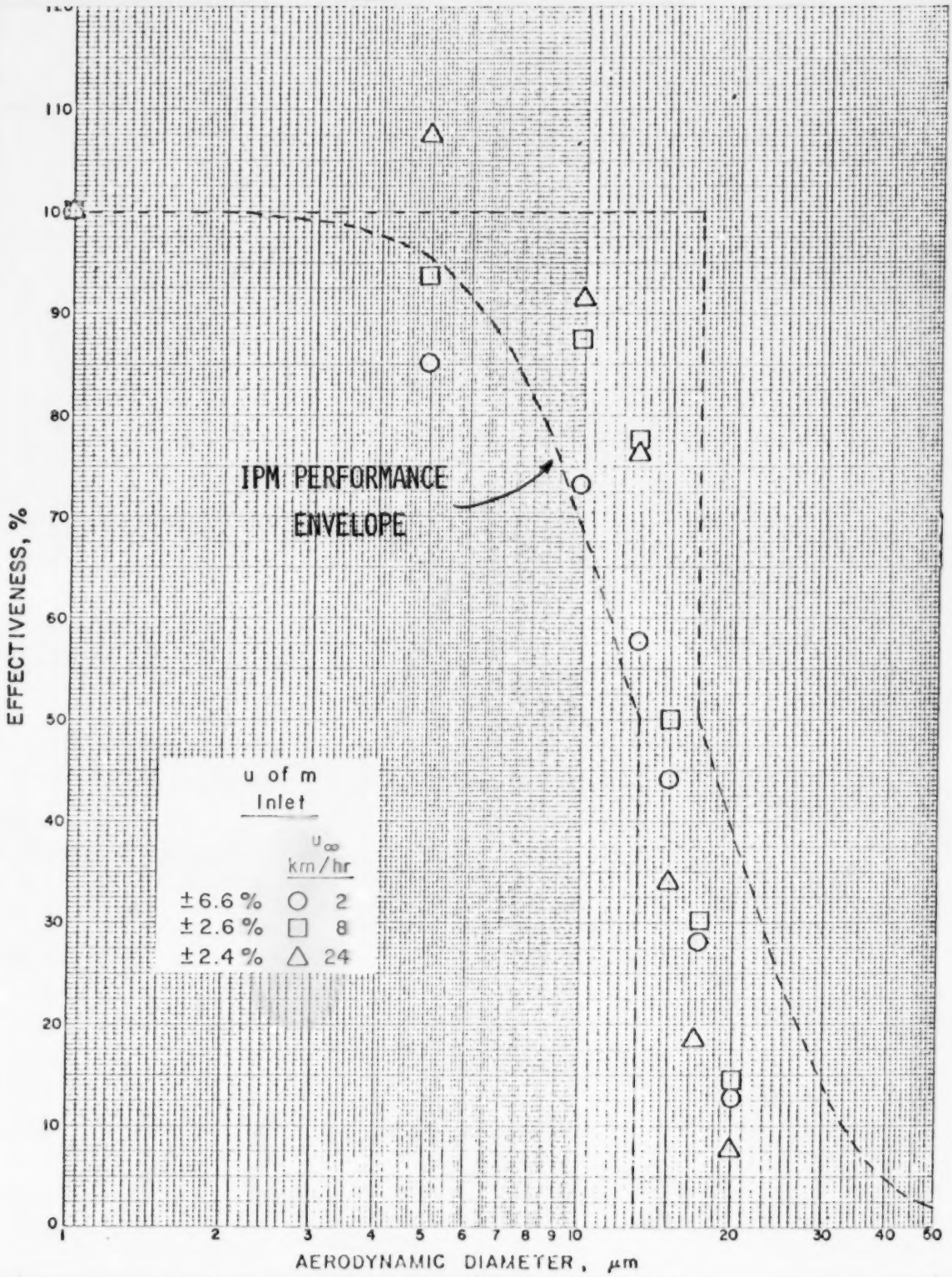


Figure 8. Performance Curves for UMLBL Inlet